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(54) Title: A TUNABLE LASER SOURCE WITH AN INTEGRATED WAVELENGTH MONITOR AND METHOD OF OPERATING SAME

(57) Abstract

    A wavelength monitor is provided based on the transmission response of an optical filter. The monitor provides feedback to the laser enabling it to lock to any given wavelength within its tuning range. The invention is also a process for integrating the wavelength monitor directly on chip with a variety of tunable semiconductor lasers. The invention also comprises a method for controlling the wavelength of a tunable laser by using a wavelength monitor to measure the output light and provide feedback to a control system. The laser and wavelength monitors are integrated together on a single indium phosphide chip. The wavelength monitor comprises a filter with a wavelength dependent transmission function and a pair of detectors. One detector is illuminated with light that has passed through the filter and the other provides a reference to measure the input intensity. Taking the ratio of the filtered light level to the unfiltered light provides a wavelength dependent signal. The filter is designed such that the transmission function is monotonic and varies from a minimum at one extent of the laser's tuning range to a maximum at the other extent.

# A TUNABLE LASER SOURCE WITH AN INTEGRATED WAVELENGTH
# MONITOR AND METHOD OF OPERATING SAME

5       This invention was made with Government support under Grant No.
N00014-96-1-6014 awarded by the Office of Naval Research. The Government
has certain rights in this invention.

*Related Applications*

10          The present application is related to U.S. Provisional Patent Application,
serial no. 60/122,194, filed on March 1, 1999.

## Background of the Invention

15  *1.      Field of the Invention*
        The invention relates to the field of semiconductor lasers, and in particular
to tunable semiconductor lasers.

*2.      Description of the Prior Art*

20          There are a variety of semiconductor laser designs in which the
wavelength can be tuned by current injection into a section which has some
spectral filtering characteristic. Examples of these are moderately tunable
devices such as the distributed Bragg reflector laser, which consists of a gain
section, a phase control section and a grating mirror, and widely tunable lasers

25  that employ Vernier effect tuning like the sampled grating distributed Bragg
reflector lasers. In all of these devices precise control of the tuning current is
requir d to achieve th  desired output wavelength. The amount of current

required to achieve a given wavelength can vary with the device temperature and also with aging. Over time as the laser ages changes in the leakage current and the carrier lifetime in the tuning sections cause the wavelength to drift. This variation in the tuning characteristics requires the use of some sort of feedback

5 control system in order for such tunable lasers to be used in applications where precise wavelength control must be maintained such as dense wavelength division multiplexed (WDM) communications systems.

Single wavelength devices such as distributed feedback lasers are also subject to wavelength drift. For these devices simple wavelength lockers are

10 used with temperature or current feedback to control the wavelength of the laser. However these wavelength lockers are only capable of maintaining the laser wavelength on a single channel which makes them useless as multiple-channel tunable lasers.

Tunable semiconductor lasers are important components for next

15 generation dense wavelength division multiplexed fiber optic networks.

What is needed is frequency stable, tunable laser module whose output frequency does not change over time. The device should be integrated on a chip, compact and cost effective. It should have a wide tuning range and be usable in high speed data transmission under direct modulation in multichannel

20 dense WDM networks.

## Brief Summary f th Inv ntion

What has been developed is a wavelength monitor based on the

transmission response of an optical filter for use in controlling the wavelength of a

5  tunable laser. This monitor can provide feedback on the laser's wavelength over

a wide tuning range enabling it to also lock the device to any given wavelength or

channel within its tuning range. It can also be used in combination with

conventional external lockers to more precisely tune to a particular wavelength

within a given channel.

10  The invention is also a process for integrating the wavelength monitor

directly on chip with a variety of tunable semiconductor lasers. This results in a

significantly more compact and cost effective device.

The invention comprises a method for controlling the wavelength of a

tunable laser by using a wavelength monitor to measure the output light and

15  provide feedback to a control system. In the preferred embodiment the laser and

wavelength monitor are integrated together on a single indium phosphide chip.

The technique is useful for control of lasers that are tuned by current injection

into sections which have a bandgap energy, which is greater than the lasing

wavelength.

20  The wavelength monitor comprises a wavelength filtering element and a

pair of detector elements. In one embodiment these elements are combined by

using detectors of different bandgap arranged in series. In others a separate filter

with a wavelength dependent transmission function is placed in front of the

d tectors. In some of these embodiments this separate filter is designed as a

wavelength dependent splitter to provide an output beam that translates laterally

from one detector to the other as a function of wavelength (much like a prism); in

other embodiments the laser output is first split into two beams, and a

wavelength dependent transmission filter is placed only in one of these prior to

5    illuminating the detectors. In all cases, taking the difference between in the

photocurrents in the two detectors, and normalizing by dividing by the sum,

provides a measure of the integrated laser's wavelength. In all cases, the net

filtering function is designed such that the normalized difference current is

monotonic and varies from a minimum at one extent of the laser's tuning range to

10   a maximum at the other extent. This approach can provide channel identification

across this entire band of wavelengths, and it can supplement or replace the

function of existing external wavelength lockers that only lock within the span of

one channel.

The invention having been summarized can be better visualized by turning

15   to the following drawings wherein like elements are referenced by like numerals.


## Brief Description of the Drawings

Fig. 1 is a perspective schematic of a tunable laser fabricated according to

the invention.

20   Fig. 2 is a graph of wavefunction intensity showing the overlap of two

mode interference waveguide modes with a laser mode in a TMI waveguide

section as a function of lateral dimension.

Fig. 3a is a side cross-sectional view of an active section of the laser.

Fig. 3b is a side cross-sectional view of a passive section of the laser.

Fig. 4 is a perspective schematic of another embodiment of a tunable laser fabricated according to the invention in which a buried heterostructure is provided.

Fig. 5 is a graph of the normalized detector response as a function of
5      wavelength for the embodiment of Fig. 4 showing sinusoidal wavelength dependence.

Fig. 6 is a graph of fiber launched power and detector current as a function of drive current for the embodiment of Fig. 4 with fixed tuning currents.

Fig. 7a is a schematic of another embodiment of a tunable laser including
10     series connected detectors.

Fig. 7b is a graph of the photocurrents from two detectors shown as a function of wavelength.

Fig. 8 is a schematic diagram of another embodiment in which the wavelength monitor is implemented with external or nonintegrated components.

15     Fig. 9 is a top plan schematic view of still another embodiment of the invention using an external wavelength monitor implementation of a dielectric filter in a planar lightwave circuit platform.

Fig. 10 is a schematic diagram of an embodiment in which reflection from a wavelength dependant dielectric film is used to implement the wavelength
20     monitor.

Fig. 11 is a schematic diagram of an embodiment in which reflection from the wavelength dependant dielectric film is used to implement the wavelength monitor as in the case of Fig. 10, but without the use of a beam splitter.

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The invention and its various embodiments can be better understood by turning to the following d tailed description of the illustrated embodiments. It is to be expressly understood that the invention as defined in the following claims is not to be limited by the illustrated embodiments.

5

## Detailed Description of the Preferred Embodiments

Tunable semiconductor lasers are important components for next generation dense wavelength division multiplexed fiber optic networks. The wide tuning range, and ability for high speed data transmission under either direct or

10      external modulation, of sampled grating, distributed Bragg reflector (SGDBR) lasers makes them especially attractive for use in multichannel dense WDM networks. These lasers tune over wide wavelength ranges by employing Vernier effect tuning. Wavelength control in these devices requires the alignment of reflection peaks from the front and back mirrors with the cavity mode at the

15      desired wavelength. This entails control of four separate tuning currents to achieve complete wavelength coverage over the entire tuning range. Using feedback on the output wavelength and intensity, it is possible to lock the device at the optimum operating point for a given wavelength.

Existing devices for monitoring the wavelength and output power of a

20      tunable laser are too complicated and expensive for practical application. What has been devised is a compact integrated wavelength monitor that can be fabricated on chip with a tunable laser to provide feedback on the wavelength and output power. In another embodiment there is an external version of the same monitor which is low cost and highly stable.

In the preferred embodiment the apparatus of the invention is comprised of a SGDBR laser coupled to a wavelength dependent splitter and a pair of integrated detectors. A schematic of the device is shown in Fig. 1. The laser, generally denoted by reference numeral 10, is a 3μm wide ridge waveguide

5    device which is comprised of four separate elements. These include two sampled grating DBR mirrors 12a and 12 b and sections for gain control 14 and phase control 16. By controlling the injection current into gain control 14 and phase control 16, laser 10 can be made to tune over more than 40 nm with continuous wavelength coverage. At the output 18 of the back mirror section

10   12b, the laser waveguide is asymmetrically coupled into a two mode interference (TMI) waveguide 20. At the end of the TMI section 20, there is a Y-branch splitter 22 that divides the light into a pair of output detectors 24a and 24b. This ratiometric design results in a compact easily fabricated wavelength monitor, generally denoted by reference numeral 26.

15       The generalized transverse active device structure as shown in side cross-sectional view of Figs. 3a is comprised of a thick higher bandgap energy waveguide layer 28 with an offset multiquantum well active region 30. Waveguide 30, which in the illustrated embodiment is a 400 nm, 1.4Q waveguide, is disposed on a 300 nm n-type buffer layer 32. The thick high

20   bandgap waveguide layer 28 is necessary for good carrier-induced index change in the tuning sections, which are comprised of sampled grating DBR mirrors 12a and 12 b and sections for gain control 14 and phase control 16. In the case of the active section of Fig. 3a, an InP etch stop layer 34 is disposed on waveguide layer 28 on which strained quantum well active layer 30 is in turn disposed. In

the case of a passive section, layers 34 and 30 are omitted. Nonabsorbing

passive elements as shown in the side cross-sectional view of Fig. 3b are form d

by selectively removing the quantum wells from on top of the waveguide 28. A p-

type InP ridge 36 is then disposed on quantum well layer 30 in the case of an

5    active section as shown in Fig. 3a or on waveguide 28 in the case of a passive

section as shown in Fig. 3b. A 100 nm InGaAs contact layer 38 is then disposed

on top of ridge 36. The use of the offset quantum wells 30 allows the formation

of active and passive sections in a single waveguide without having to perform a

butt joint regrowth. This allows the device to be fabricated with only two

10    _____ chemical vapor deposition (MOCVD) growth steps.

Light coupled from the laser 10 into the TMI section 20 excites the two

lowest order lateral modes of the waveguide as shown in the graph of Fig 2.

These modes propagate with different phase velocities which leads to a

characteristic beating in a modal superposition pattern. The beat length is

15    dependent on the difference in the propagation constants for the two modes

which each depend on the wavelength of the light. At the end of the TMI section

20, a Y-branch splitter 40 splits the light into a pair of output waveguides 42a and

42b with a wavelength dependent splitting ratio. By making the TMI section 20

long enough to contain several beat lengths, the splitting ratio becomes

20    increasingly sensitive to the wavelength of the laser 10.. The total power out of

the back facet 18 of the laser 10 can be determined by summing the currents

from both detectors 24a and 24b. The wavelength dependent signal is

normalized to this sum to remove the power dependence.. This results in a

sinusoidal output signal that varies with wavelength. The TMI wav guide 20 is

wide at its ends to enhance the optical coupling and tapers quadraticly along its

central interference section to increase the modal dispersion. The splitter 40

employs a Y-branch design to divide the incoming optical power into two output

waveguides 42a and 42b. The output waveguides 42a and 42b contain the

5      photodetectors 24a and 24b respectively which measure the divided light

intensity. Large detector sizes are used to prevent saturation of their absorption

by the high optical power levels that are experienced in the photonic integrated

circuit.

The detector signals can then be coupled to a conventional processor or

10     controller circuit (not shown) where the control signal is generated from the ratio

of the detection signals, normalized if needed, and coupled to laser 10 to provide

the appropriate tuning control. The manner in which the data or signals are

processed according to the teachings of the invention is conventional and

therefore will not be further illustrated in detail. It is contemplated that the

15     processor or controller circuit will be integrated or assembled into the chip or may

be externally provided as shown in Fig. 8 below.

A key advantage of the TMI wavelength monitor 26 is that it can be

fabricated using many of the steps required for tunable lasers 10, making it

relatively easy to integrate on chip. There are eight main steps in the fabrication

20     procedure for the SGDBR laser with the integrated wavelength monitor. First, a

base structure 44 is grown using near atmospheric MOCVD with

tertiarybutlyphosphine and tertiarybutylarsine for the group V sources. The

transverse structure for the active and passive sections are shown in Figs. 3a

and 3b respectiv ly. Passiv  sections are formed by selectively etching off the

cap layer (not shown) and then the quantum wells 30. The gratings 12a and 12b

are then formed for the laser mirrors using a dry etch process.

In the second MOCVD step, a 2 μm InP upper cladding layer 36 and a

100nm InGaAs contact layer 38 are regrown. The ridge waveguides are etched

5    to within 200nm of the waveguide layer using a methane-hydrogen-argon

_____ (MHA RIE) etch. A wet etch ($HCL:H_3PO_4$) is then used to

remove the last 200nm and stop on the waveguide 28. The dry etch is done to

maintain the straight side walls in the curved waveguide section, while the final

wet etch compensates for the nonuniformity in the MHA RIE and provides for

10   consistent etch depth. A $SiN_x$ layer (not shown) is used to passivate the surface

with self-aligned openings on the ridge tops for the Ti/Au p-contacts 13. Isolation

between the adjacent laser sections and between the detectors is achieved by

etching off the contact layer 38 and performing a deep proton implant(not

shown). This step is essential for providing good isolation between the reversed

15   biased detectors 24a and 24b and the forward biased laser sections 10. In the

final steps, the device is lapped to 100 μm thick, and a backside contact (not

shown) is deposited before cleaving and mounting.

It is also possible to fabricate this device with a buried heterostructure. In

this case the Y-branch splitter and detector pair of Fig. 1 can still be used, but in

20   Fig. 4 a tapered waveguide 46 with two detectors 48a and 48b placed on each

side are used in place of the Y-branch splitter 40. The output mode from the TMI

waveguide 20 is then imaged on the region between the detectors 48a and 48b

to provide a position sensitive output difference count. The fabrication is similar

to the ridge process except that the ridge is etched prior to regrowth and the  tch

proceeds until it has cut completely through the waveguide 28. Then in the

regrowth InP material is grown up around the ridge completely burying it. The

contact layer 38 is then patterned so that it only covers the area directly over the

buried ridge 36 and a proton implantation step is also used to prevent lateral

5    current spreading.

When the wavelength of the laser 10 is tuned, the two detectors 48a and

48b provide complementary sinusoidal responses for wavelength monitoring.

Taking the ratio of the difference between the detector currents to the sum of the

detector currents provides a single monotonically varying signal which is

10    wavelength dependent and power level independent as shown in the graph of

Fig. 5. The sum of the two detector currents can be used to monitor the laser

output power as shown in the graph of Fig. 6. The current from detector 48a is

shown by line 64, the current from detector 48b is shown by line 66, and their

sum is shown by line 68. Dots 70 show the measured launched power in the

15    output fiber. It is important for both this and the operation of the wavelength

monitor 26 that the photodiode response is as close to linear as possible and that

both detectors 48a and 48b are well matched. Again the detection signals are

processed by a signal processor or controller (not shown) according to

conventional means consistent with the teachings of the invention.

20    Another potential embodiment for the wavelength monitor 26 would

employ a pair of detectors 24a and 24b similar to those shown in either Figs. 1 or

4 in which the bandgap of the absorbing section of the two detectors was

different. One detector 24a would have a bandgap which was low enough to

provide full absorption of the incident light so that it's detection curr nt would be

proportional only to the photon density. The other detector 24b would have a higher bandgap such that the absorption would vary with the wavelength of the light. This would be accomplished by using a short detector length with a band gap energy slightly greater than the shortest wavelength of light. The detection

5      response would then vary monotonically with wavelength. Again the detection signals are processed by a signal processor or controller (not shown) according to conventional means consistent with the teachings of the invention.

Another potential embodiment for the wavelength monitor 26 would employ a pair of detectors 49a and 49b with different bandgaps placed in series

10     along a single passive waveguide continuing from the output 18 of laser 10 as illustrated in Fig. 7a. As can be seen, this embodiment eliminates the need for the Y-branch splitter as well as the dispersive TMI dispersive waveguide section. The back detector 49b is highly absorbing across the entire band while the front detector 49a has an absorption edge beginning near the shorter wavelength side

15     of the tuning range as illustrated in Fig. 7b. This front detector 49a is relatively short, so that it only partially absorbs the incident light, thus transmitting about half of it in the center of the laser's tuning range. Thus, the net photocurrent would appear as in Fig. 7b for the two detectors. Therefore, as in other cases an unambiguous wavelength readout can be obtained by using the ratio of the

20     difference to the sum of the two currents. An advantage of this embodiment is that it is much shorter than ones requiring the TMI and Y-branch sections.

It is also possible to implement the wavelength monitor 26 using an external device as shown in the schematic diagram of Fig. 8. In this embodiment a dielectric filter 50 is used with a wavelength dependent response and a pair of

detectors 52a and 52b. A 10/90 fiber optic splitter 54 is used to tap some of the output light from the laser 10 on optic fiber 57 which is split using a 3 dB coupler 56 into two separate optic fibers 58a and 58b . One fiber 58b is coupled directly to a reference detector 52b. Detector 52b monitors the laser power. The other

5   fiber 58a has a collimator 60 with the filter element 50 in front of it. This gives it a wavelength dependent response. The signal from detector 52a is divided in a controller circuit 62 coupled to laser 10 by the signal from the reference detector 52b to provide a power independent signal.

The external device illustrated in Fig. 8 can also be implemented in a very

10   compact manner using a hybrid technology shown in Fig. 9. The laser is mounted accurately onto a planar lightwave circuit (PLC) platform 72 such that the power emitted by either the back 74 or front 76 facet is coupled into the PLC waveguide 78. If the front facet 76 used, the light from the laser 10 is passed first through a wavelength independent 5/95 tap 80 such that the majority of the light

15   can be used as output. Light from back facet 78 is transmitted entirely to monitor 26 without tapping. The monitored or tapped portion of light is then passed through a wavelength independent 3 dB splitter 82 which couples the pair of photodetectors 84a and 84b also bonded to the PLC platform 72. Before detector 84b is a wavelength filtering element 86 is inserted. This can be

20   implemented by a either a waveguide coupler filter or the waveguide can be cut through and the filter described in Fig. 8 is placed in the groove with an index matched epoxy. Again the detection signals are processed by a signal processor or controller (not shown) according to conventional means consistent with the teachings of the invention.

Another embodiment for the wavelength monitor 26 is diagrammatically

shown in Fig. 10. This embodiment employs a filter coating 88 deposited on the

back facet 74 of the laser 10. A Y-splitter 90 is used to divide the light into two

paths. One path 94a is incident on a reference detector 92a for measuring the

5       light intensity and the other path 94b reflects off of the back facet 74 at an angle

of incidence less than the critical angle. Thin film facet coating 88 with a

wavelength dependent reflectivity is used. The intensity of the reflected light

varies with the wavelength providing a signal which is used for wavelength

monitoring in detector 92b. Again the detection signals are processed by a signal

10      processor or controller (not shown) according to conventional means consistent

with the teachings of the invention.

This method is also used in the embodiment schematically shown in Fig.

11 without a Y-splitter 90 by letting the light diffract so that a portion of the light is

incident on the facet 74 at an angle greater than the critical angle, $\theta_c$, and a

15      portion is incident at an angle less than the critical angle, $\theta_c$. The laser output

may be curved somewhat to facilitate separation of these two portions and to

prevent feedback into the laser section. Light from back facet 74 is reflected by

wavelength dependent facet coating 88 at an angle to facet 74. The portion of

light which was subject to total internal reflection 98 is collected by a reference

20      detector 100a and the portion which is subject to a wavelength dependent

reflection is collected by a second detector 100b. The function of facet coating

88 might also be accomplished by an integrated grating similar to those formed in

the tunable laser.

Many alterations and modifications may be made by those having ordinary skill in the art without departing from the spirit and scope of the invention. Therefore, it must be understood that the illustrated embodiment has been set forth only for the purposes of example and that it should not be taken as limiting the invention as defined by the following claims. For example, notwithstanding the fact that the elements of a claim are set forth below in a certain combination, it must be expressly understood that the invention includes other combinations of fewer, more or different elements, which are disclosed in above even when not initially claimed in such combinations.

The words used in this specification to describe the invention and its various embodiments are to be understood not only in the sense of their commonly defined meanings, but to include by special definition in this specification structure, material or acts beyond the scope of the commonly defined meanings. Thus if an element can be understood in the context of this specification as including more than one meaning, then its use in a claim must be understood as being generic to all possible meanings supported by the specification and by the word itself.

The definitions of the words or elements of the following claims are, therefore, defined in this specification to include not only the combination of elements which are literally set forth, but all equivalent structure, material or acts for performing substantially the same function in substantially the same way to obtain substantially the same result. In this sense it is therefore contemplated that an equivalent substitution of two or more elements may be made for any one of the elements in the claims below or that a single element may be substituted for two or more elements in a claim.

Insubstantial changes from the claimed subject matter as viewed by a person with ordinary skill in the art, now known or later devis d, are expressly

contemplated as being equivalently within the scope of the claims. Therefore, obvious substitutions now or later known to one with ordinary skill in the art are defined to be within the scope of the defined elements.

5     The claims are thus to be understood to include what is specifically illustrated and described above, what is conceptionally equivalent, what can be obviously substituted and also what essentially incorporates the essential idea of the invention.

We claim:

1      1.      A method of operating a tunable laser comprising:

2      sampling light from said laser;

3      splitting said sampled light into a first and second path;

4      detecting said light in said first path;

5      filtering the intensity of said light in said second path in a manner which is

6   dependent on wavelength;

7      detecting said light in said second path after being filtered;

8      producing a wavelength dependent control signal from a ratio of intensity

9   of said light detected in said first and second paths; and

10      tuning said laser by feeding back said wavelength dependent control

11   signal to said tunable laser.

1      2.      The method of claim 1 wherein filtering the intensity of said light in

2   said second path monotonically filters said light as a function of wavelength.

1      3.      The method of claim 2 wherein said tunable laser has a tuning

2   range, and wherein the degree of filtering the intensity of said light in said second

3   path is varied between extremums corresponding to said tuning range of said

4   laser.

1    4.    The method of claim 1 wherein filtering the intensity of said light in

2    said second path is performed by creating a wavelength dependent, beat pattern

3    between two modes of light.


1    5.    The method of claim 4 where creating a wavelength dependent,

2    beat pattern between two modes of light is performed for several beat lengths of

3    said two modes of light prior to splitting said two modes light into said first and

4    second paths.


1    6.    The method of claim 4 wherein splitting said sampled light into a

2    first and second path comprises splitting said two modes of light into said first

3    and second path with a wavelength dependent splitting ratio.


1    7.    The method of claim 6 further comprising determining total power

2    output from said laser by summing detected light in said first and second paths.


1    8.    The method of claim 7 where producing a wavelength dependent

2    control signal from a ratio of intensity of said light detected in said first and

3    second paths is performed by normalizing said control signal with said total

4    power output.

1     9.    The method of claim 4 wherein splitting said sampled light into a

2    first and second path comprises transmitting said two modes of light to two

3    segmented detectors, wherein detecting said light in said first and second paths

4    comprises detecting said light in said two segmented detectors to provide two

5    complementary sinusoidal detection signals, and wherein producing a

6    wavelength dependent control signal comprises generating said control signal as

7    a ratio between the difference of said two complementary sinusoidal detection

8    signals and the sum of said two complementary sinusoidal detection signals.


1     10.    The method of claim 1 where detecting said light in said first path

2    comprises detecting said light with a detector with a bandgap energy low enough

3    to provide substantially full absorption of said light, and where filtering and

4    detecting said light in said second path comprises in combination detecting said

5    light with a short detector with a bandgap energy slightly greater than the shortest

6    wavelength of said light +so that absorption varies with wavelength of said light.


1     11.    The method of claim 1 wherein filtering the intensity of said light

2    comprises reflecting said light off a back facet of said tunable laser through a

3    wavelength dependent coating disposed on said back facet.


1     12.    The method of claim 1 where splitting said sampled light into a first

2    and second path comprises diffracting said light back onto a back facet of said

3   laser so that a portion is totally internally reflected and a portion reflected back

4   from a wavelength dependent coating disposed on said back facet.


1       13.    A method of operating a tunable laser comprising:

2           sampling light from said laser;

3           generating two signals from said light sampled from said laser, which two

4   signals are wavelength dependent and distinguished from each other by a

5   different dependence on wavelength;

6           generating two detected signals corresponding to said two signals;

7           combining said two detected signals to produce a wavelength dependent

8   control signal; and

9           tuning said laser by feeding back said wavelength dependent control

10  signal to said tunable laser.


1       14.    An apparatus for controlling a tunable laser comprising:

2           a wavelength-dependent optical device to produce two optical signals from

3   light sampled from said laser, which two optical signals are wavelength

4   dependent and distinguished from each other by a different dependence on

5   wavelength;

6           a first and second detector to detect said two optical signals to generate

7   two corresponding electrical detection signals; and

8    a processor coupled to said to first and second detector to generate a

9    control signal from said two corresponding electrical detection signals by which

10   said tunable laser is tuned.


1    15.   The apparatus of claim 14 wherein said a wavelength-dependent

2    optical device comprises a two mode interference waveguide.


1    16.   The apparatus of claim 15 further comprising a wavelength-

2    dependent Y-branch splitter coupled between said two mode interference

3    waveguide and said first and second detector.


1    17.   The apparatus of claim 15 where said first and second detector

2    comprises a segmented detector and further comprising a flared waveguide

3    coupling said two mode interference waveguide and said segmented detector.
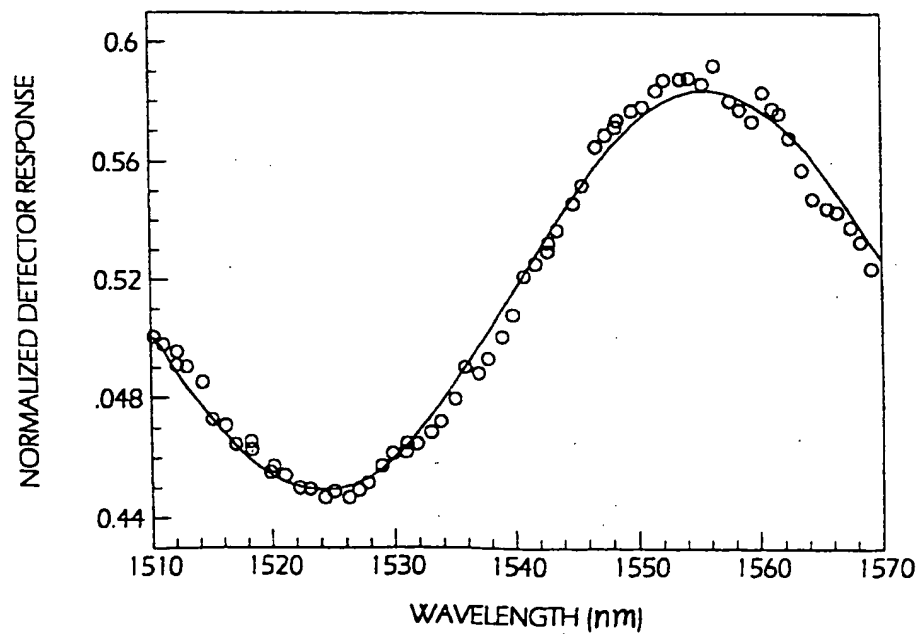

1    18.   The apparatus of claim 14 where said a wavelength-dependent

2    optical device comprises a wavelength-dependent optical filter.


1    19.   The apparatus of claim 14 where said a wavelength-dependent

2    optical device comprises a wavelength-dependent optical coating.

1 20. Th apparatus of claim 19 further comprising a splitter, said splitter

2 directing a first portion of light from said laser to said first d tector and directing a

3 second portion of light from said laser to said coating, said second detector

4 detecting light reflected from said coating.


1 21. The apparatus of claim 19 further comprising a diffractor, said

2 diffractor directing a first portion of light from said laser into said coating such that

3 said first portion is totally internally reflected and directing a second portion of

4 light from said laser into said coating such that said second portion of light from

5 said laser is reflected through said coating to said second detector.


1 22. The apparatus of claim 14 wherein said laser is semiconductor

2 laser and wherein said wavelength-dependent optical device is integrally

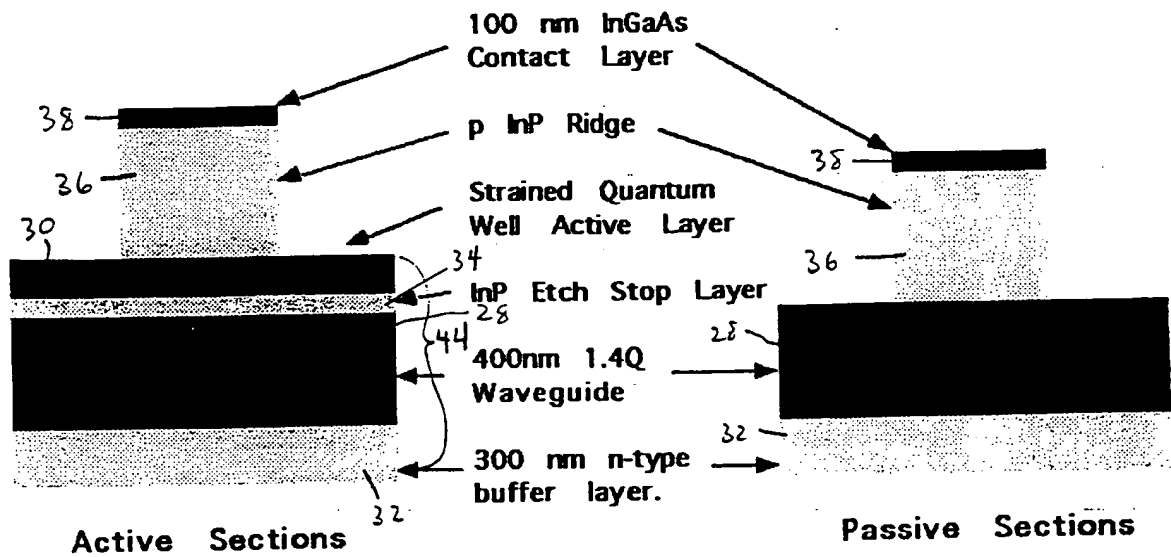3 fabricated with said semiconductor laser on a common chip.

Fig. 1



Detectors

24a

42a
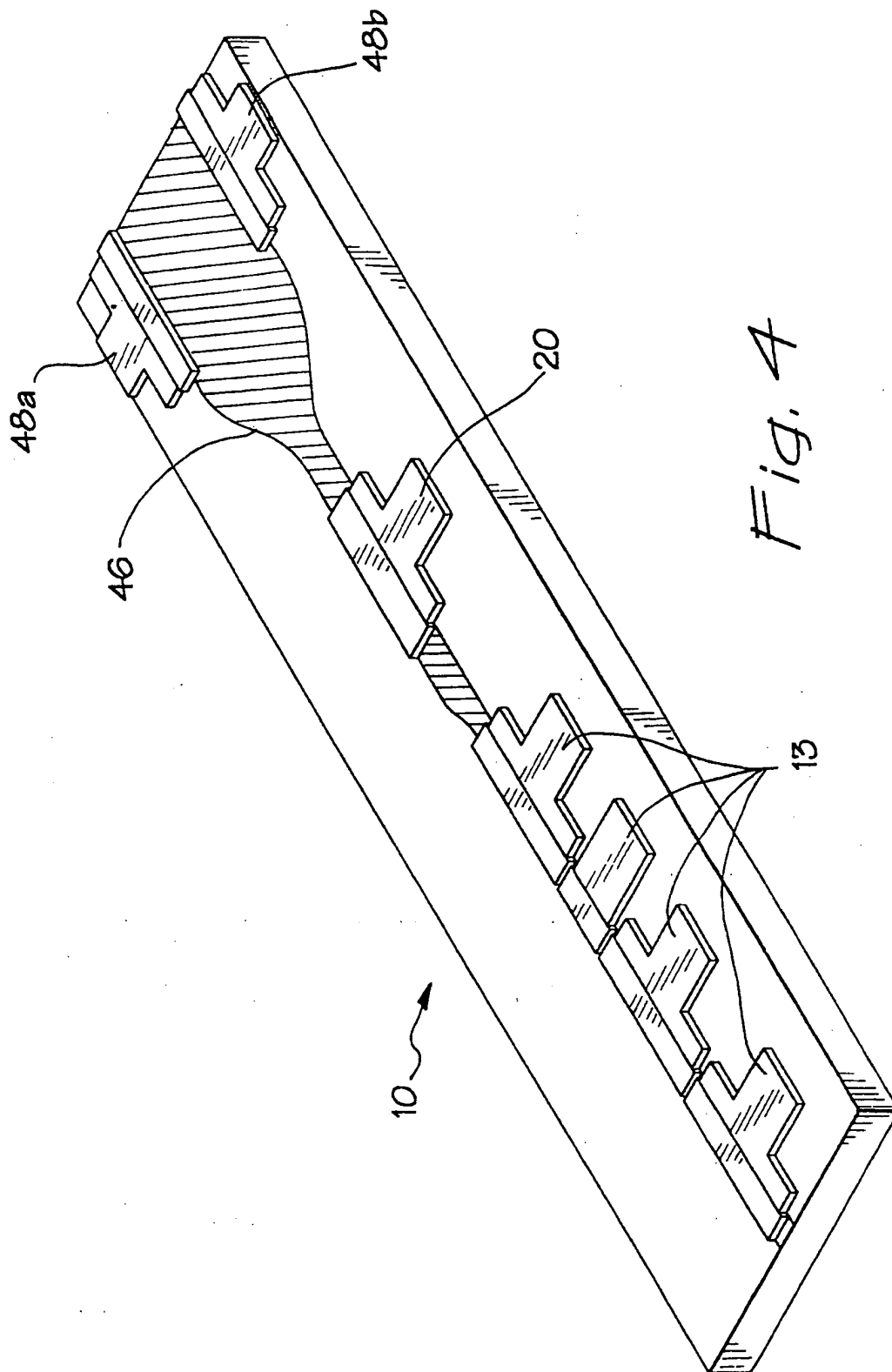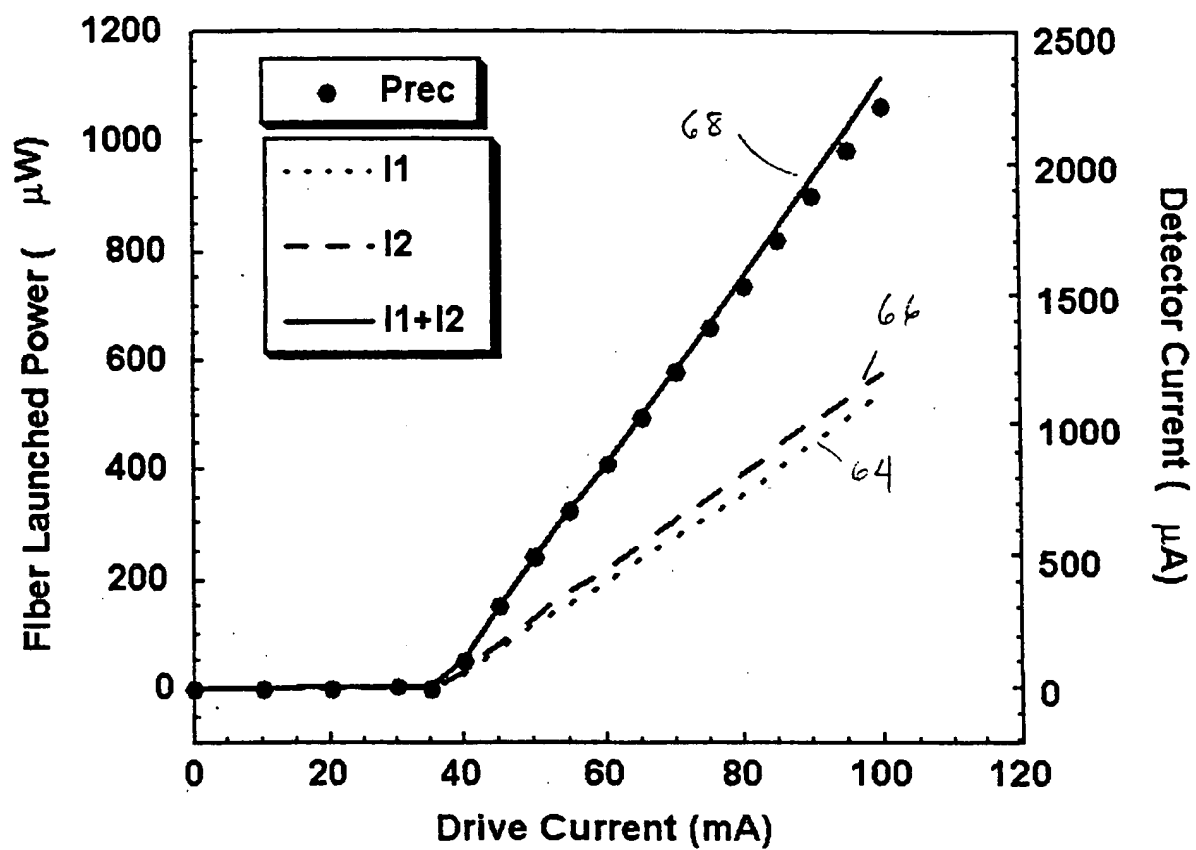
TMI Waveguide
20

18

10

Sampled Grating
Mirrors

12b

12a

24b

42b

Y-Branch
22

Phase Control
16

Gain Section
14

13

*Fig. 2*



*Fig. 5*

100 nm InGaAs
Contact Layer

p InP Ridge

38

36

30

Strained Quantum
Well Active Layer

34

InP Etch Stop Layer

28

44

400nm 1.4Q
Waveguide

38

36

28

300 nm n-type
buffer layer.

32

32

**Active Sections**

**Passive Sections**

Fig 3a

Fig 3b

48b

48a

46

20

13

10

Fig. 4
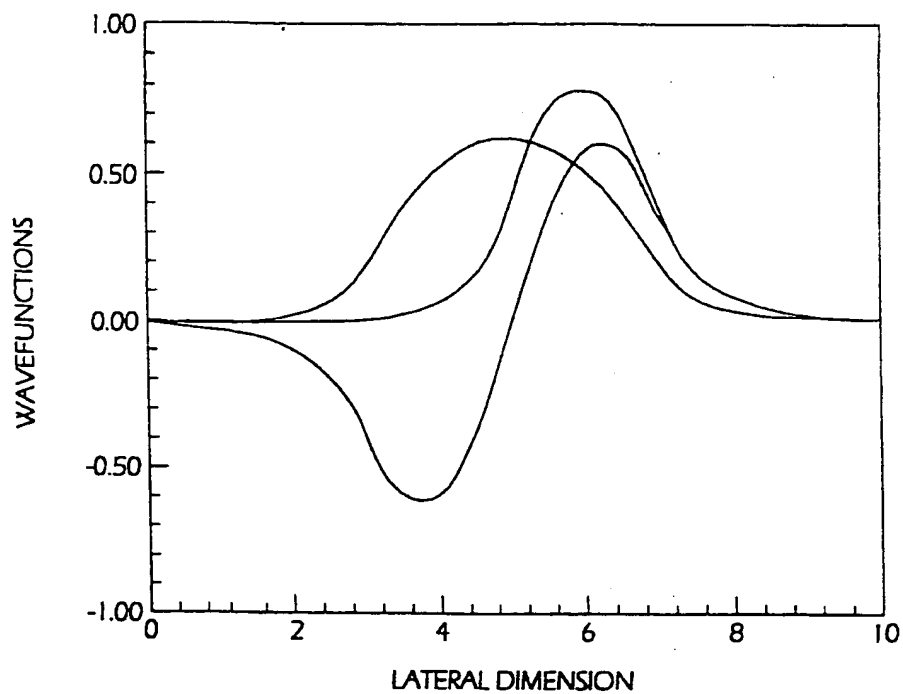
Fig 6

**Fig. 7a**



**Fig. 7b**

Fig. 8

Fig. 5

10/90 Splitter

Controller

Tunable Laser

Signal Photodiode

Filter

3 dB Coupler

Reference Photodiode

Figure 8 External Wavelength Monitor Implementation Using Dielectric Filter Element

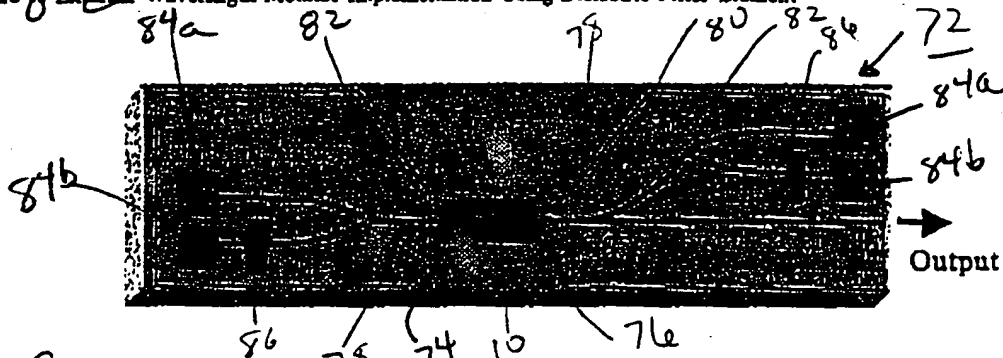84a   82   78   80   82   86   72

84a

84b

84b

Output

86   78   74   10   76

Figure 6 External Wavelength Monitor Implementation Using Dielectric Filter Element in a PLC Platform

PLC implementation of 8

Fig. 10

Tunable Laser 10

Wavelength Monitoring Detector 100b

Reflective Filter 88

74

$\Theta_c$

Light totally reflected 98
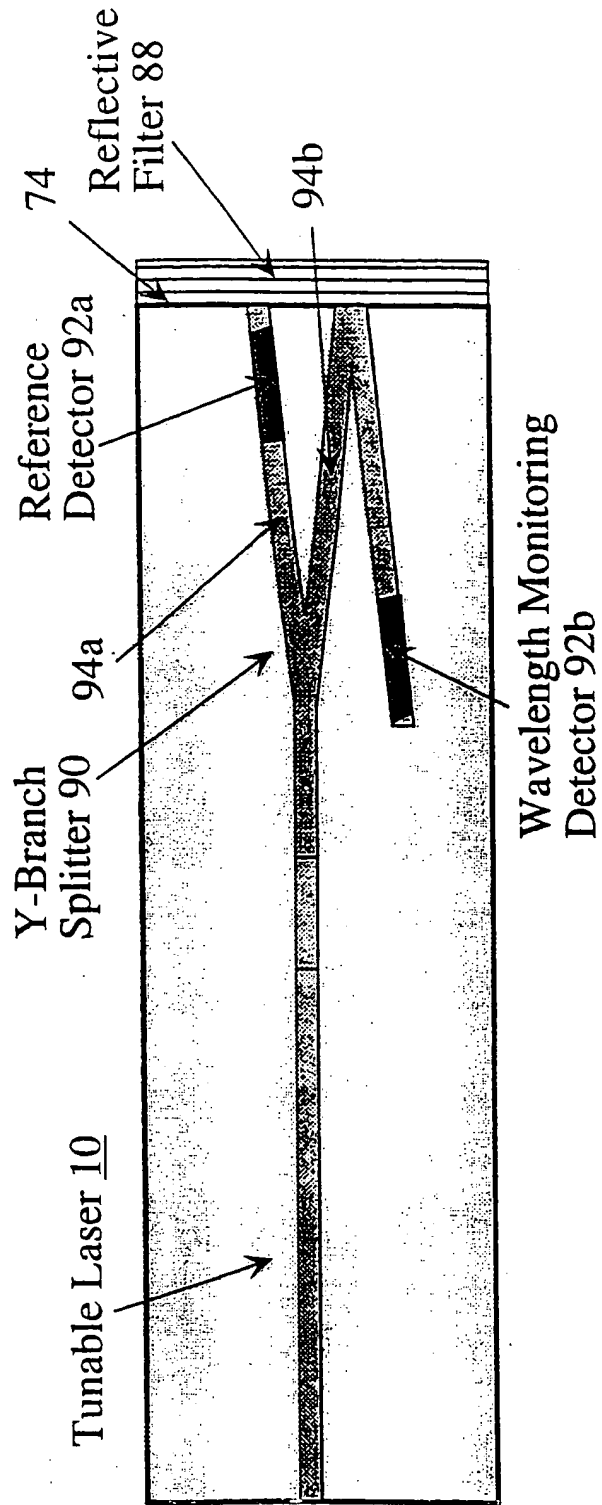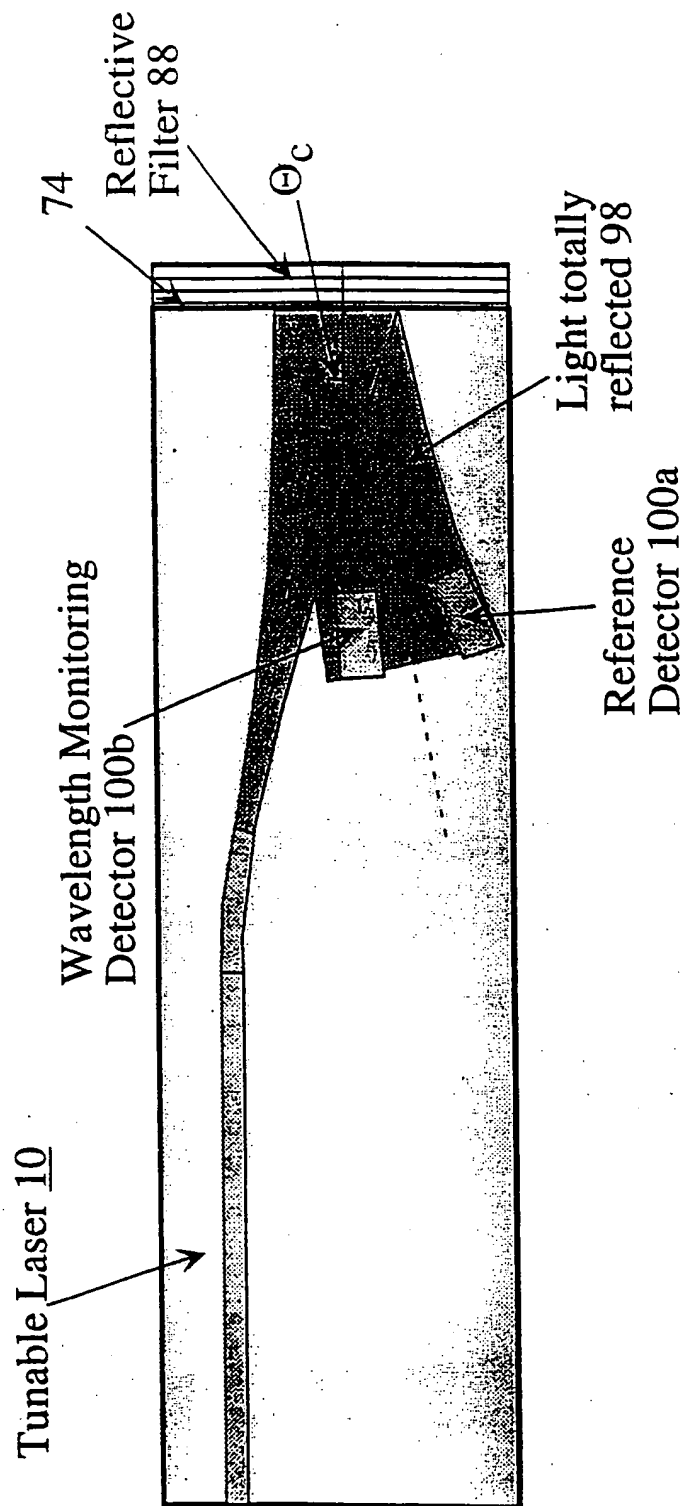
Reference Detector 100a

FIG. 11

Block Diagrams Outlining Generic Types



*Fig 12a* 1. Wavelength Dependent Splitter (Figs 1, 4)

Tunable laser — 10

Wavelength-dependent splitter — 20, 22
e.g., TMI & Y-branch

Detector-1 (λ) — 24a, 46a — I1(λ)

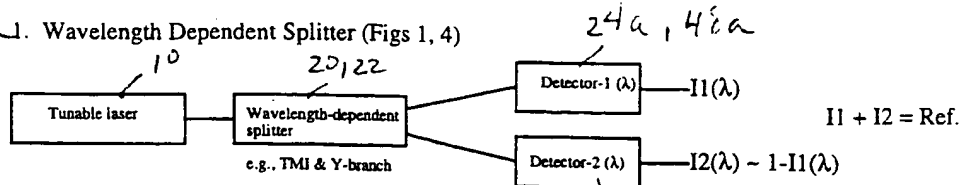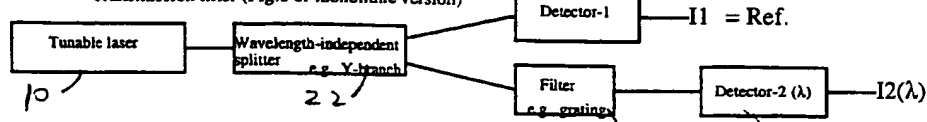Detector-2 (λ) — 24b, 4?b — I2(λ) ~ 1-I1(λ)

I1 + I2 = Ref.

*Fig 12b* 2. Simple Wavelength Independent Splitter (Filter afterwards)

a. Filter between splitter and monitoring detector

-- Transmission filter (Fig.8 or monolithic version)

Tunable laser — 10

Wavelength-independent splitter e.g. Y-branch — 22

Detector-1 — 49a — I1 = Ref.

Filter e.g. grating — 50

Detector-2 (λ) — 49'a — I2(λ)

*Fig 12c*

-- Reflection filter (Figs. 10, 11) — 22

Tunable laser — 10

Wavelength-independent splitter e.g. Y-branch

Detector-1 — 92a, 100a — I1 = Ref.

Filter e.g. grating — 74

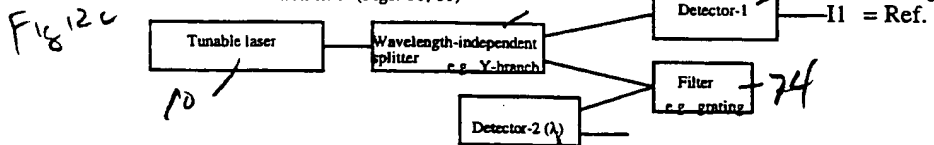Detector-2 (λ) — 92b, 100b

I2(λ)

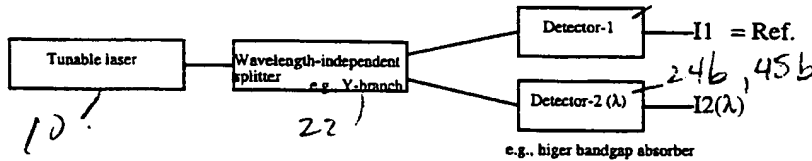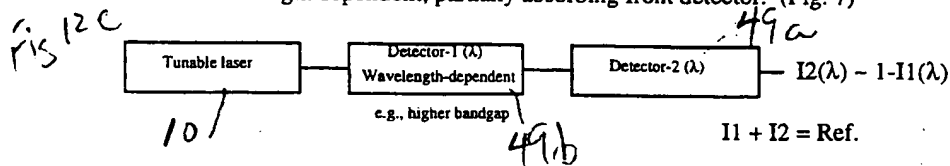*Fig 12d* 2b. Detector-2 is itself wavelength dependent (higher bandgap):
(Figs 1 & 4 without TMI but with higher bandgap detector-2) — 24a, 45a

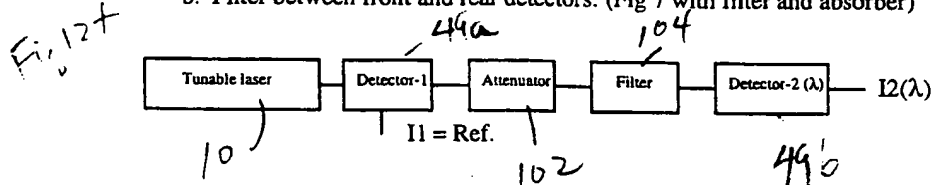Tunable laser — 10

Wavelength-independent splitter e.g. Y-branch — 22

Detector-1 — I1 = Ref.

Detector-2 (λ) — 24b, 45b — I2(λ)
e.g., higer bandgap absorber

3. In-line Monitor with no splitter:

a. Wavelength dependent, partially absorbing front detector: (Fig. 7)

*Fig 12e*

Tunable laser — 10

Detector-1 (λ) Wavelength-dependent e.g., higher bandgap — 49a, 49b

Detector-2 (λ) — I2(λ) ~ 1-I1(λ)

I1 + I2 = Ref.

b. Filter between front and rear detectors: (Fig 7 with filter and absorber)

*Fig 12f*

Tunable laser — 10

Detector-1 — 49a — I1 = Ref.

Attenuator — 102

Filter — 104

Detector-2 (λ) — 49'o — I2(λ)

F-12